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STRENGTH BEHAVIOR OF ADHESIVE BONDS UNDER IMPACT LOADS

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16. Abstract

An optical electric assembly with a photodiode, a hammer, and a pendulum ram testing device was used in determining the impact strength of several commercial adhesive bonding materials applied to metals. Bonding performance under impact stresses was better in adhesive materials with a greater deformation margin than in those with lower elastoplastic characteristics.

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STRENGTH BEHAVIOR OF ADHESIVE BONDS UNDER IMPACT LOADS

C. Hahn[1]

The deformation and strength properties of adhesives are more or less /311*
dependent on the stress rate according to condition and structural makeup. With large rate changes the characteristic strength values of metallic bonded parts, however, can no longer be regarded as constant, so that the bonding strength no longer suffices as a parameter for the behavior of the adhesions. By determination of additional parameters it was possible, in the breaking process of cemented bonds even at great load rates, to characterize and describe the effects of important joint parameters, like joint partial strength, overlapping length, adhesive layer thickness and elastic-plastic adhesive behavior, upon breaking. It has been shown that, through impact loading, the adhesives with good deformation properties exhibit better strength properties in the metallic joint than bonding agents with poorer elastic-plastic behavior. The strength of the bond can be greatly influenced by choice of joint geometry.

1. Introduction

The successful introduction of metal adhesives as a joining process assumes knowledge about parameters which determine the strength behavior. Today most of them are known on the basis of extensive investigations and practical experiences with their effects, such that the possibilities of use which are offered, after weighing the advantages and disadvantages of the adhesive against other joining processes, can be evaluated relatively well. The application of certain characteristic strength values determined in the laboratory nevertheless frequently causes difficulties. This is based to a considerable extent on the fact that different and often more complex stress behaviors occur in actual practice than the experimentally obtained data would indicate. Thus stress rates as they appear in the determination of bond strength, occur relatively seldom in reality. Nevertheless, bonded structural elements in airplanes and

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*Numbers in the margin indicate pagination in the foreign text.

vehicles - the principal field of use of metal adhesives - are, while in use, exposed to dynamically changing and often sharp stresses.

2. Parameters of Adhesive Behavior Under Impact Loads

As a rule the strength properties of industrial materials are defined under sudden strain by the breaking load necessary to destroy specific test samples. Since the breaking load allows no detailed assertion about the breaking process, its information content is limited, and in many cases it does not suffice for a clear evaluation of the behavior of a material or a bond under impact stress. To be able to characterize the breaking process better, therefore, one needs further characteristic magnitudes to describe it. Primarily, breaking tension and breaking elongation serve that purpose. To determine them, it is necessary to plot the force pattern during the fracture process against the breaking displacement. From the force-displacement pattern, then, with known sample dimensions and reference sizes for elongation, these characteristic values and the specific load can be determined. Moreover, the latter may be divided into a working portion, which causes only elastic deformation of the sample, and, in a given case, one which produces plastic deformation.

In the scope of this study, the force-displacement pattern during the breaking process of impact-loaded, one-notched, overlapped metal bonds was plotted, and the parameters explained schematically in Figure 1 were evaluated to describe the breaking process.

The force F_1 allows determination of the maximum mean joint stress and the maximum "bond strength" appearing during the breaking process with known sample dimensions. Both calculated average stresses, however, permit no direct inferences about the actual stresses appearing in the sample, since the geometry of the one-cut, overlapped unions determines the stress distribution both in the joint part and joint region in impact-loading in many respects. One time, owing to the asymmetrical form of the union, there is a superposition of tractional and bending stresses, at other times, also depending on the bond geometry, there are attendant characteristic phenomena of widening impact waves, or reflections. Hence it is difficult to make statements about instantaneous stress distribution in the test piece. In presentation of the experimental results in the scope of these explanations, the interposition of the characteristic values largely has /312 been relinquished. As long as no practicable measuring procedure exists, it seems more important to the designing engineer to plot the extent of their influence according to their effects and thus to afford a feeling for true stress and adhesive measurement.

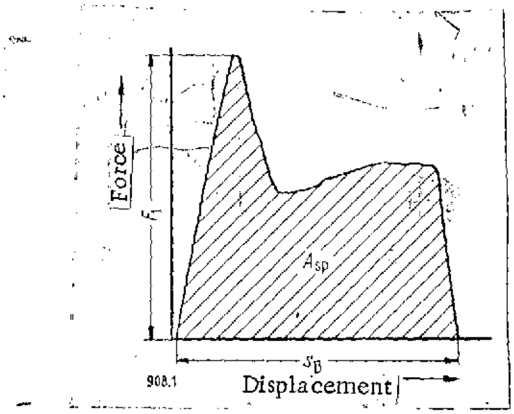


Figure 1. Force-Displacement Pattern Diagram of the Breaking Process of Impact-Stressed, One-Notched Overlapped Metal Bondings. F_1 maximum force, s_B displacement up to fracture, A_{sp} specific breaking load.

3. Experimental Structure for Impact Motion and Impactive Impulse Tests

For the experiments a customary pendulum striking device was provided, with additions which permitted recording the force-displacement pattern during breaking both at the point of impact (crosshead-stud) and in the region of mounting. Figure 2 shows an overall view of the test device.

The break displacements were recorded with an optical-electrical measuring device, which essentially consists of a photodiode working on the Schottky barrier principle, a light source and a shutter fastened to the hammer of the pendulum impact mechanism. The diode is negatively charged and works as a current generator, whose signal varies within a range of 10^{-13} to 10^{-3}W linearly with the incident light intensity. The shutter varies the incident light on the diode by passing between the light source and the diode as the hammer to which it is attached swings through , thus varying the diode current flow and current voltage drop which correlates the load resistance in the circuit with the hammer movement. Figure 3 shows the principle of the measuring apparatus.

The force was measured by the deformation of a dynamometer rod holding the sample. An undistorted reproduction of the force curve acting at the clamp presupposes that the measurement was finished before the reflected part of the shock wave at the end of the rod arrived again at the SMS. The transit time of the shock wave in this case must be longer than the breaking time of the sample. With the propagation rate c_0 of the wave in the rod and the rod length l, the transit time t of the primary shock wave is calculated by

$$t = \frac{2l}{c_0} \approx 300 \cdot 10^{-6} \text{ s.}$$

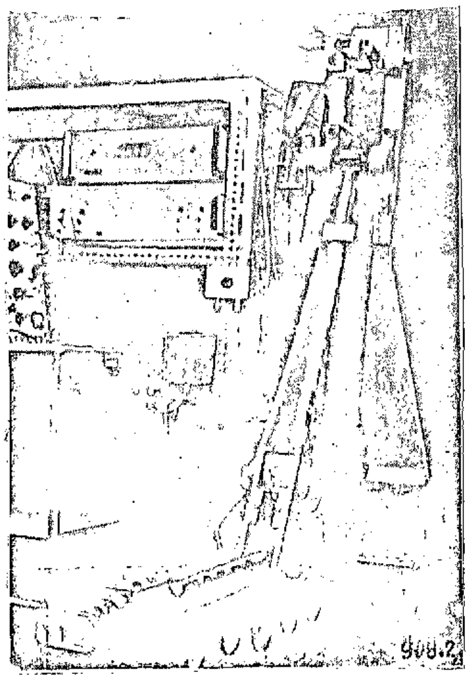


Figure 2. Experimental Apparatus for Impact Tests on Metal Bondings.

Figure 4 shows the force pattern /313 at the measurement receiver in the dynamometer rod when a steel ball strikes the free end of the rod serving as sample clamp, with the reflection signal after some 300 microsec.

With longer breaking times, which occur especially with small (low) testing speeds/rates or large load absorption of the sample, the reflection waves after 300 microsec. cause a distinct falsification of the plotted force pattern, so that a determination of the breaking load by planimetry of the Force-Displacement diagram was no longer possible. The force calibration was done by static loading of the dynamometer rod. This is permissible, since the relaxed modulus M_R in metals has to be replaced only at essentially greater stress rates, i.e., temporal tensional and stretching changes in the region of about 10^{-10} sec., by the unrelaxed modulus

$$M_N = \frac{\tau_\sigma}{\tau_\varepsilon} M_R$$

[1]; τ_σ indicates the time constant for elongation changes at constant tension and τ_ε the time constant for tensional changes at constant extension.

4. Experimental Results

4.1 Effect of Strength of the Joint Part on the Strength of Adhesions

The effect of the material of the joint part on the strength of cemented bonds at low test rates is known [2]. With a rising yield point of the joint part, the bond strength increases. With loading above the yield point, the adhesive has increasingly greater stress imposed on it, without a corresponding increase in force being recorded.

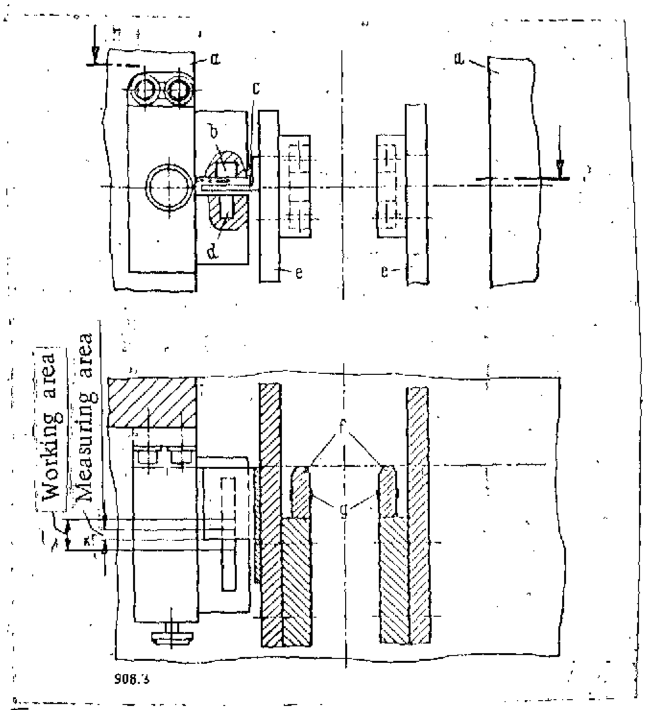


Figure 3. Principle Sketch of the Optical-Electrical Measuring Device. a, Pendulum impact assembly; b, lamp; c, shutter; d, photodiode; e, hammer; f, peen; g, stretch measuring strip (SMS).

This higher adhesive stresses caused by plastic joint-part deformations does not take into account the bond strength, since for its determination only the force necessary to rupture the bond is called upon. The breaking load is another matter. It is a measurement for the force applied over the displacement pattern, but does not permit inferences about the 2 sizes.

The relationship between breaking load and joint-part yield point therefore can not be characterized so easily as that between bonding strength and joint-part yield point.

Researches with the deep-drawing plate St 12.03 have shown that, to reach the joint-part yield point, a certain amount of strength in the joint layer is required. If this is not furnished, then the bond breaks as the load increases without joint-part displacement remaining. The load needed to break the bond is relatively small. If the joint layer is only partially damaged in exceeding the yield point, then in the further breaking pattern there occurs more or less large residual joint-part deformation and a correspondingly high load absorption by the adhesion.

Hence, in respect to the load absorbtion of a cemented bond, the strength and deformation properties of the metal have increased significance.

Although the influence of the stress rate on the strength of cemented bonds can be attributed in quasi-static stress primarily to the dependence of the rate on the deformation and strength properties of the adhesive, with large rate variations it is also based on rate speed-related changes in the behavior of the metallic joint-part material.

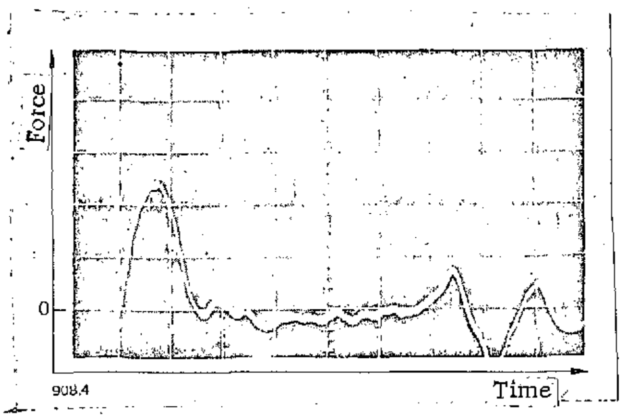


Figure 4. Time course of the Measurement Signal at the Stretch Measuring Strip (SMS) Upon Impact of a Steel Ball on the Free End of the Dynamometer Rod Acting as a Clamp. Arrival of the reflection wave at the SMS after about 300 microsec. 1, Time: 1 Div. = 50 microsec.; 2, force: 1 Div. = 3000 N; 3, Div. means: distance of the coordinate gridlines.

As is known from numerous studies, as the stress rate increases, the yield point and breaking strength of the metal rises. For yield point in question in the bounds of this analysis, we state that, with a change in the stress rate of around 5 to 6 powers of ten, the yield point increases independently of temperature, T by about the factor of 1.2 - 3.0, Figure 5 [3].

This means that the breaking forces in impact stressing are essentially greater than those in quasistatic stressing. The plastic joint-part deformation critical to the break initiation in bondings with the deep-draw plate St. 12.03 appears first at average joint-part stresses of around 650 - 700 N/mm^2, depending on overlap and adhesive. This corresponds in the present sample measurements and the chosen joint geometry (length of overlapping l_u = 12 mm) to a "bond strength" of approximately 110 N/mm^2 as against some 26 N/mm^2 in quasistatic stressing.

When using a joint-part material of greater strength, the breaking force increases if the joint layer is strong enough, so that the specific stressings also increase as with small stressing rates. The average tension levels which are needed to initiate breakage and which are comparable to joints made of St 12.03 are approximately 800 N/mm^2 or 130 N/mm^2 ("bond strength"). /314

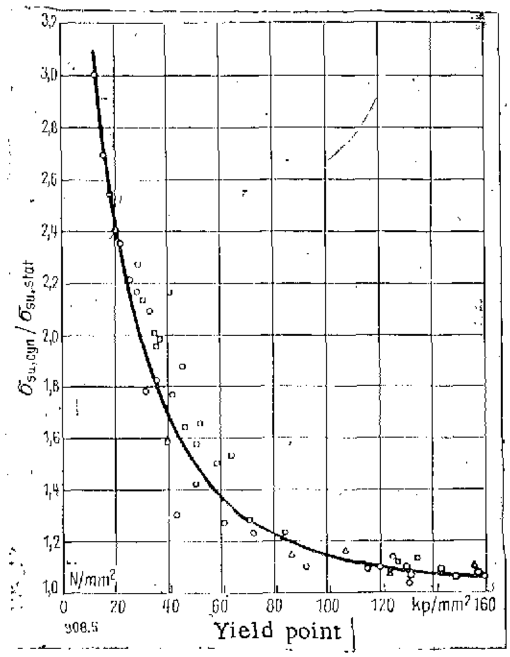
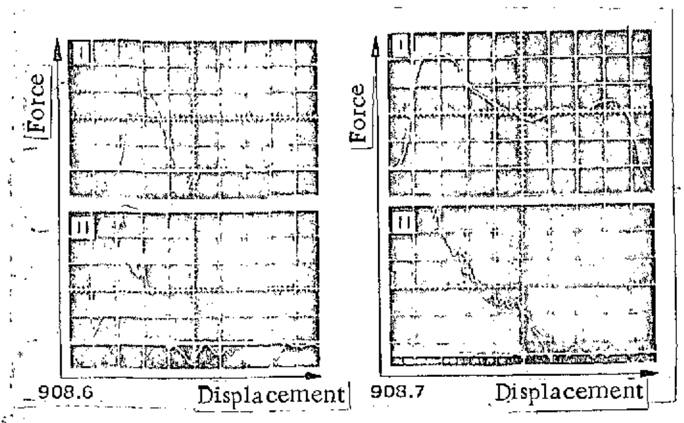


Figure 5. Yield Point Increase in Various Metallic Industrial Materials Under Dynamic Stress. $\sigma_{su,dyn}$ Yield point under inpact stressing; $\sigma_{su,stat}$ yield point under quasistatic stress. Abscissa, yield point, kilopond/mm^2; ord., N/mm^2.

Simultaneously, however, the plastic joint-part deformations and the breaking load decrease. This is evident from Figures 6 and 7 for bondings with the adhesive FM-1000, Figure 7. With unfavorable choice of joint geometry (too small overlapping) or brittle adhesives, even at slight joint-part strength the yield point is not reached under certain circumstances because the fracture already occurred. In these cases the breaking procedure and the parameters serving to describe it hardly change, as can be seen from Figure 6 for bonds with adhesive HT-424.

The tests of the effect of the joint-yield point on the breaking process of impact-like stressed bonds are valid not only for joints out of steel, but also for aluminum and its alloys. With joint-yield-point increases, plastic displacements at like geometry and strength of joint layer decrease, and the average tensions in the joint and joint region increase. Different adhesive behavior occurs in the force-displacement-pattern primarily in different breaking patterns and breaking loads. The maximum force which appears, indicated in Figure 1 by F_1, is in comparision - aside from cases in which the break occurs before the yield point is reached - a parameter which characterizes the joint component.



Figures 6 and 7. Effect of the Yield Point on the Breaking Process From Impact-Stressed, One-Notched, Overlapped Metal Bonds. I) Bonded material: St 12.03; II) bonded material: St 52; force:

1 Div. $\hat{=}$ 6000 N; displacement: 1 Div. $\hat{=}$ 0.075 mm. 1, Figure 6. Metal Bonding with Adhesive HT-424. a, Length of overlap: L_u = 12 mm; b, impact velocity: v_s = 5.41 m/sec.; c, joint thickness: a = 2 mm; d, joint width: b = 21 mm. 2, Figure 7. Metal Bonding with Adhesive FM-1000. a, Length of overlap: L_u = 12 mm; b, impact velocity: v_s = 5.41 m/sec.; c, joint thickness: a = 2 mm; d, joint width: b = 21 mm.

4.2 Effect of Overlapping on the Strength Behavior of Adhesives

The constructive formation of the joint surface has a great effect on the strength of cemented bonds [2]. This general statement applies also to the behavior of metal adhesions under impact stresses. By increasing the overlap, the joint surface serving to conduct the force is enlarged, and the strength of the bond is thereby improved. Under stress the bond fails at greater forces or, on passing the yield point, with greater joint deformations. In the first case the increase in breaking load corresponds somewhat to that of the overlapping length, so that a nearly constant specific breaking load can be estimated. As soon as plastic joint-component displacement appears, an increase of the specific breaking load can be expected.

The force pattern during the breaking process, aside from cases of stress in which, owing to insufficient impact energy in the first impact phase, the force pattern is defined primarily by oscillations, is expressed primarily the strength and deformation properties of the joint component. The extent of overlapping and the adhesive properties determine the moment of failure.

So in stressing adhesions with a relatively brittle adhesive and a long overlapping, there appear force patterns comparable to those in bonds with a highly elastic bonding agent and a short overlapping, Figures 8 - 10.

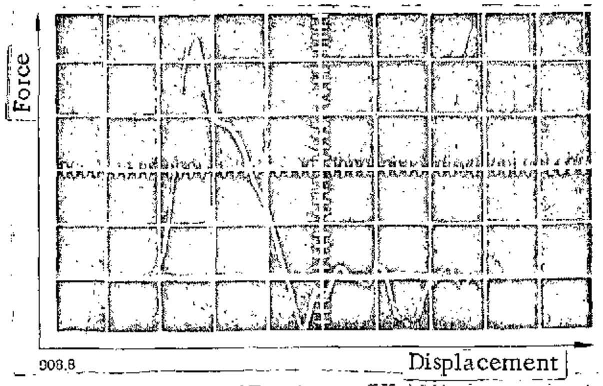


Figure 8

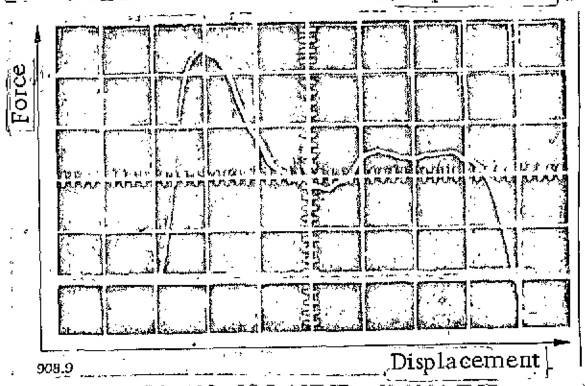


Figure 9

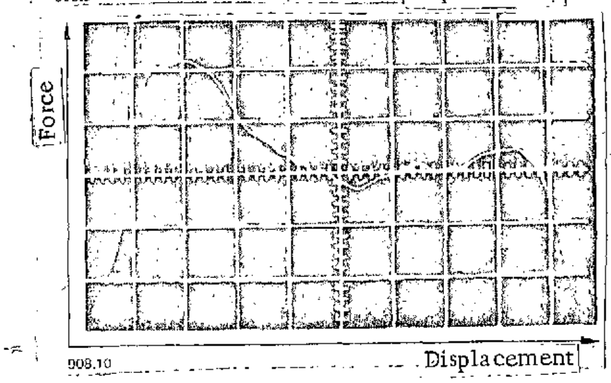


Figure 10

Figures 8 - 10. Force-Displacement Diagram of the Breaking Process of Different Impact-Stressed, One-Grooved, Overlapped Metallic Bonds. 1, Force: 1 Div. = 6000 N; 2, displacement: 1 Div. = 0.075 mm; 3, joint material: St 12.03; 4, joint thickness: a = 2 mm; 5, joint width: b = 21 mm; 6, impact speed: v_s = 5.41 m/sec.

Figure 8. Adhesive HT-424; overlap length: L_u = 12 mm. Figure 9. Adhesive HT-424; overlap length: L_u = 24 mm. Figure 10. Adhesive FM-1000; overlap length: L_u = 12 mm.

This indicates that, with a brittle adhesive, by choosing choice a suitable joint geometry even with occasional impact stress, one can attain strength qualities similar to those of a highly elastic bonding agent. However, limits are set by the different breaking behavior (fissuring and crack propagation) of brittle bonding agents in comparison to highly elastic adhesives. An additional argument for increasing overlap is that the maximum joint component tensions, under equal external loads, decrease with overlapping. For a bond with long overlaps to reach a critical tension, it has to be loaded more than with short. In general, it can be said that in impact stressing one should prefer adhesives with good elastic-plastic properties and that enlarging the overlap, up to a certain limit, always improves the strength quality of a bond under impact stress.

4.3 Effect of Adhesive Layer Thickness on Bond Strength

The influence of the thickness of the adhesive stratum on the strength of cemented bonds in static and quasistatic stressing is known from the references [2; 4]. The binding moment increases with the adhesive layer thickness. At the same time the joint component's resistance to deformation decreases, so that the elastic-plastic adhesive quality becomes more important. Breakage sets in at lower forces, while the breaking patterns increase as a result of the improving "deformability" of the joint layer, Figures 11 and 12. Therefore the breaking load is relatively independent of adhesive layer thickness.

In bonds with the adhesive HT-424 at thin adhesive layers, changes in thickness do not affect the breaking force as much as with bonds with the adhesive Araldit AW 106. The same holds for the breaking displacement. This is understandable when one considers the great difference in strength and deformation properties of the adhesive substances.

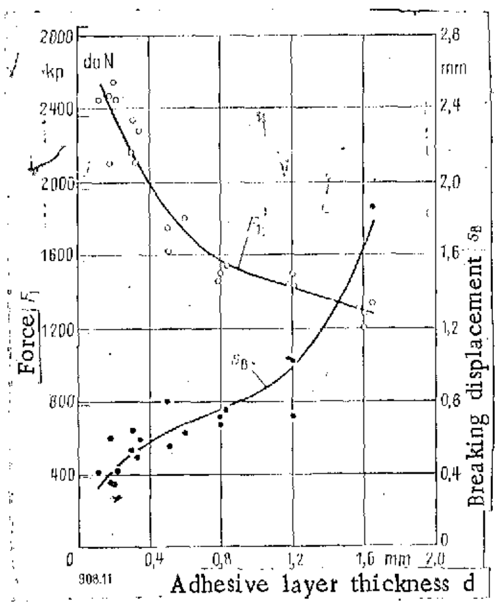


Figure 11. Influence of the Adhesive Layer Thickness d_1 on the Breaking Force and the Breaking Displacement in a Metallic Bonding. 1, Material: St 37; 2, adhesive: Araldit AW 106; 3, overlap length: L_u = 12 mm; 4, joint component thickness: a = 3 mm; 5, joint component width: b = 21 mm; 7, impact speed: v_s = 5.41 m/sec.

Therefore, the adhesive layer thickness has more effect when, with thin layers, the joint component yield point is exceeded and plastic joint component deformation occurs, while with thicker layers, the displacement remains essentially limited to the adhesive joint. In this case a greater decrease of the breaking load can be expected. /315

For practical purposes the recommendation may be made that the adhesive layer thickness be kept small for impact-stressed plate bonds, so that, among other things, the tensions in the joint component during the breaking process exceed the critical level for plastic joint component deformations and an important part of the impact energy is taken up by the joint component. This does not hold for adhesive bonds, in which one can exclude from the outset plastic joint component displacements and in which the deformations during the breaking process are limited to the joint layer.

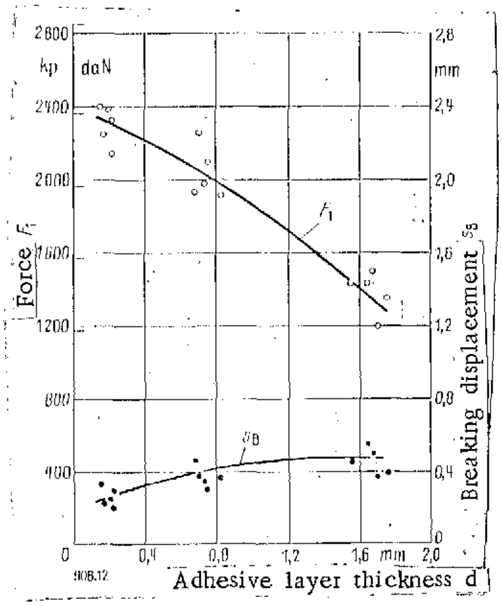


Figure 12. Effect of Adhesive Layer Thickness on the Breaking Force and the Breaking Displacement in a Metallic Bonding. 1, Material: St 37; 2, adhesive: HT-424; 3, overlap length: L_u = 12 mm; 4, joint component thickness: a = 3 mm; 5, joint component width: b = 21 mm; 6, impact speed: v_s = 5.41 m/sec.

4.4 Effect of High Stress Rates on the Strength Behavior of Bonds

Under static and quasi-static stress, the cements remain tough, that is, they stretch elastically and plasticly. As the stress rate increases, this ability to stretch decreases since the processes of molecular re-arrangement which are necessary for plastic stretching takes place comparatively slowly. If the load is imposed so quickly that no molecular re-arrangement can occur, then one must expect the cement to act brittlely. This is shown by a low level of load absorbtion and in breaking without stretching.

This statement, which holds true for the cementing substance, cannot be applied directly to its behavior in a joint. If one compares the behavior of cemented joints under quasi-static stress with their behavior under impact stress, one finds that both the forces which appear during the breaking process and the stretching of the entire joint under inpact loads are, as a rule, the largest. It is true that this is less due to differing behavior of the cementing substance than to the rate-related changes in the stretching and strength characteristics of the joint material; it shows, however, that the knowledge available today about the behavior of cementing material does not have to apply unconditionally to the behavior of the bonds.

Just how bonds react to changes in the stress rate has not been successfully determined up till now. Attempts of this sort with pendelum hammer models cannot be done on a satisfactory scale because with such models the stress factors, and thereby the stress on the sample, vary too much with the speed of the hammer.

Only through a critical hammer speed, which depends on the cross-sectional mass of the hammer as well as on the elasticity of the sample, can true impact stress and repetition of the results obtained be guaranteed. In the research undertaken, this critical speed for the selected model tests was approximately 5 m/s. Experimental results in the speed range above 4 m/s allow one to suppose that bond strength under impact loads do not react to speed changes of this order as they do to smaller speeds.

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